TECHNOLOGY AND APPLICATIONS OF ESD COATINGS BEFORE AND AFTER LASER PROCESSING

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Abstract

Protective coatings for machine parts can be economically viable if the wear is localized or if the coating material has different properties than the substrate. Technological surface layers (TSLs) are applied to objects before use, while functional surface layers (FSLs) are applied during maintenance. Laser surface modification is a field of study that involves numerous research centers worldwide. By controlling laser parameters such as power, scanning speed, and pulse duration, it is possible to create coatings with various surface properties, such as surface geometry, microhardness, stress states, or resistance to wear. One of the most common and affordable techniques for surface modification is electro-spark alloying (ESA) or electro-spark deposition (ESD), which involves using a focused stream of energy similar to laser treatment. However, electro-spark deposited coatings may have drawbacks that limit their application. To address this, the coatings can be further treated with a laser, which effectively eliminates surface defects such as scratches, delamination, and microcracks. Additionally, the laser treatment seals the coating, improving its overall performance. ESA coatings have multiple applications, including protecting new elements and restoring the properties of worn elements. ESD is a proven technique for regenerating aircraft engine and hydraulic components in specialized vehicles. The production of ESD protective coatings has also found extensive use in the automotive industry. Significant research has been conducted to assess the effect of various ESD parameters on the properties of coatings. This paper aims to determine the properties of electro-spark coatings by analyzing their microstructure, measuring their microhardness, friction force, and corrosion resistance. To carry out these tests, a Cu-Mo coating (the anode) was electro-spark deposited onto carbon steel C45 (the cathode). The resulting coatings are intended for use in increasing wear and corrosion resistance.

Keywords: Electro-spark deposition, laser processing, coatings, properties

1. INTRODUCTION

Depositing protective layers on metal surfaces frequently involves matter and energy transfer, which is accompanied by various chemical, electrochemical and electrothermal reactions. To determine the operational properties of a surface layer, it is necessary to analyze the original, technological properties of the material, the deposition method, and, particularly, the mechanism of energy accumulation inside and outside the workpiece. By controlling polarity, it is possible to remove or replace material. The process of material removal involving erosion of the stock subjected to electric discharges is called electrical discharge machining (EDM). The surface layer forming on the product improves its operational properties. The process of material growth resulting from electro-erosion is known as electro-spark alloying (ESA) or electro-spark deposition (ESD). The erosion of the anode and the spark discharges between the electrodes result in the formation of a surface layer with properties different from those of the base material [1-4]. Electro-spark deposited coatings have some disadvantages but these can be easily eliminated. One of the methods is laser beam machining (LBM); a laser beam is used for surface polishing, surface geometry formation, surface sealing or for homogenizing the chemical composition of the deposited coatings [5]. It is envisaged that the advantages of laser-treated electro-spark coatings will include: lower roughness, lower porosity, better adhesion to the substrate, higher wear and seizure resistance, higher fatigue strength due to the occurrence of compressive stresses on the surface, higher resistance to corrosion.

Coatings applied with ESA or ESD methods and then modified are characterized by features that are very beneficial in many areas of operation. Among others, they allow for achieving the desired adhesion during soldering [6], surface hardening of aluminum composites [7], modification of powder coatings [8], and alteration of the ductility of materials [9]. Additionally, they enable obtaining positive characteristics of radar camouflage [10], which results in a significant improvement in the quality of the products [11-13] and development of new improvement methods [14-16]. Moreover, the use of these coatings is a significant impulse for the further development of advanced approaches in data analysis methods, as bootstrap [17,18], which is used for statistical inference, and the description of 3D microstructures [19,20]. Therefore, the development and application of these coatings have great potential for advancing various fields of research and technology.

2. MATERIALS AND METHODS

The tests were conducted for Cu-Mo coatings produced by electro-spark deposition, which involved applying Cu and Mo electrodes with a diameter of 1 mm (the anode) on the C45 steel substrate (the cathode). Here copper constitutes the core coating material in the formation of low-friction surface layers; it also compensates for the occurrence of residual stresses. Molybdenum act as the reinforcing constituents. The coating materials, i.e. molybdenum (99.8% Mo) and copper (99.2% Cu) in the form of wire ($\phi = 1$ mm) were purchased from BIBUS Metals Sp. z.o.o. (certificate included). The coatings were electro-spark deposited on C45 steel substrate by means of the ELFA-541 made by a Bulgarian manufacturer. Base on the analyses of the current characteristics as well as the manufacturer's recommendations, it was assumed that the parameters of the ESD operation should be as follows: current intensity $I = 16$ A (for Cu $I = 8$A); table shift rate $v = 0.5$ mm/s; rotational speed of the head with electrode $n = 4200$ rev/min; number of coating passes $L = 2$; capacity of condenser system $C = 0.47$ μF; pulse duration $T_i = 8$ μs; interpulse period $T_p = 32$ μs; frequency $f = 25$ kHz. The subsequent laser treatment was performed with the aid of a BLS 720 laser system employing the Nd:YAG laser operating in the pulse mode. The following parameters were assumed for the laser treatment: laser spot diameter $d = 0.7$ mm; laser power $P = 20$ W; beam shift rate $v = 250$ mm/min; nozzle-sample distance $h = 1$ mm; pulse duration $t_i = 0.4$ ms; frequency $f = 50$ Hz.

3. RESULTS AND DISCUSSION

A Joel JSM-5400 scanning microscope equipped with an Oxford Instruments ISIS-300 X-ray microanalyzer was used to test the coating microstructure. **Figure 1** show the microstructure of electro-spark deposited two-layer Cu-Mo coatings. The layer thickness is approximately 8÷10 μm, and the range of the heat affected zone (HAZ) inside the (underlying) substrate material is about 10÷15 μm. In the photograph, the boundary line between the two-layer coating and the substrate is clear. The melting and solidifying processes during laser treatment resulted in the migration of elements across the coating-substrate interface. Laser radiation caused intensive convective flow of the liquid material in the pool and, in consequence, the homogenization of the chemical composition (**Figure 2**). In the heat affected zone (HAZ), which was 20÷50 μm thick, there was an increase in the content of carbon.

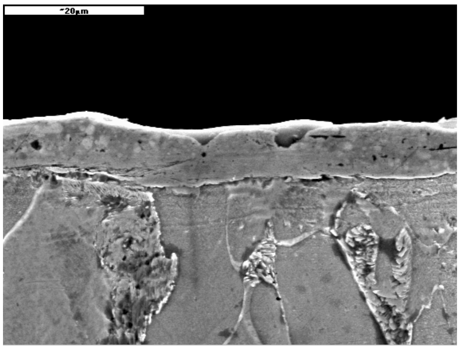


Figure 1 Microstructure in the Cu-Mo coating

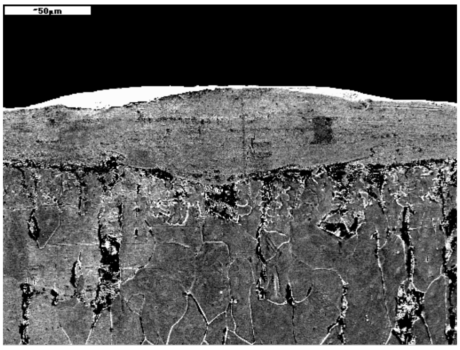
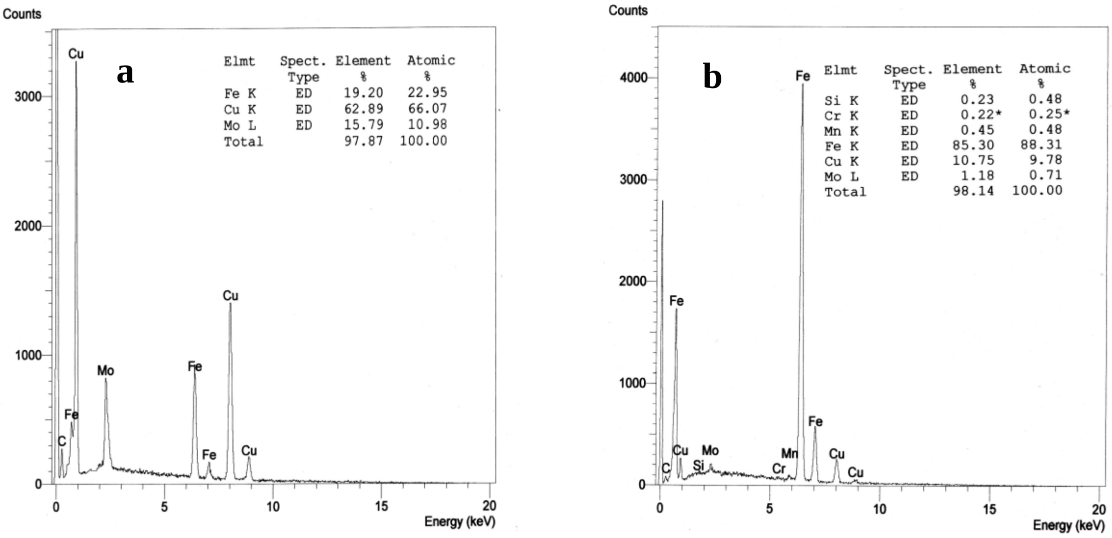


Figure 2 Microstructure in the Cu-Mo coating after laser treatment

The point analysis conducted for the outer surface of the technological surface layers (**Figure 3a**) shows high intensity of peaks of the elements present in the coating. The Cu-Mo coating contained 66.07% at. of Cu and 10.98% at. of Mo, which may testify to the mixing of the two elements and the formation of a multi-phase alloy (**Figure 3a**). The point analysis of the electro-spark coatings treated with a laser beam (**Figure 3b**) shows high intensity of iron peaks in the alloyed layers. The content of iron in the laser-treated technological surface layers was between 88% at. and 97% at. After laser treatment, the intensity of Mo and Cu peaks in the electro-spark deposited coatings was lower.



Elmt	Spect. Type	Element %	Atomic %
Fe K	ED	19.20	22.95
Cu K	ED	62.89	66.07
Mo L	ED	15.79	10.98
Total		97.87	100.00

Elmt	Spect. Type	Element %	Atomic %
Si K	ED	0.23	0.48
Cr K	ED	0.22*	0.25*
Mn K	ED	0.45	0.48
Fe K	ED	85.30	88.31
Cu K	ED	10.75	9.78
Mo L	ED	1.18	0.71
Total		98.14	100.00

Figure 3 Spectrum of an X-ray radiation for an electro-spark deposited Cu-Mo coating: a) before laser treatment; b) after laser treatment

The microhardness was determined by using the Vickers method (Hanemann tester). The measurements were performed under a load of 0.4 N. The indentations were made in perpendicular microsections in three zones: the white homogeneous difficult-to-etch coating, the heat affected zone (HAZ) and the substrate. The test results for the electro-spark deposited Cu-Mo coating before and after laser treatment are shown in diagrams in **Figure 4**. Electro-spark deposition caused changes in the microhardness of the material. The microhardness of the substrate after electro-spark deposition was on average 281 HV0.4; the same value was reported for the substrate before the process. There was a considerable increase in microhardness after depositing the heterogeneous Cu-Mo coating. The microhardness of the Cu-Mo coating was approx. 587 HV0.4, which gives increase of 110 %. The microhardness of the Cu-Mo coating in the heat affected zone (HAZ) after electro-spark treatment was 51 % higher than that of the substrate material. Laser treatment had a favorable effect on the changes in the microhardness of the electro-spark deposited of the Cu-Mo coating. There was an increase of 161 % in the microhardness of the Cu-Mo coating.

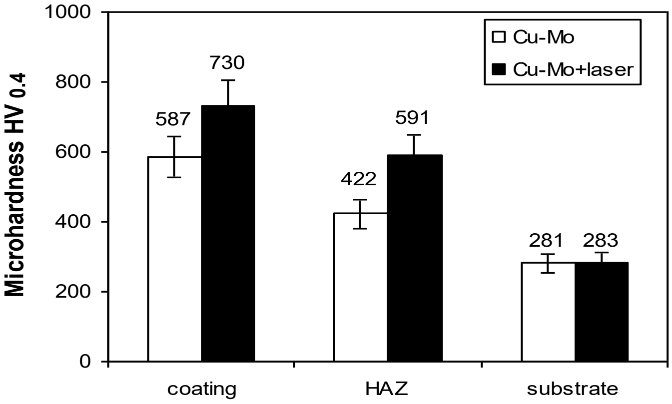


Figure 4 Results of the microhardness tests for the Cu-Mo coating before and after laser treatment

The coefficient of friction for Cu-Mo coating before and after laser treatment was determined using a T-01- pin on disc type tribological tester. The tester enables continuous measurement of the friction force at a set load. The pin of ϕ4 x 20 mm was made of medium-carbon steel with a hardness of 27 HRC. The testing was performed at the following parameters: load Q = 10 N, rotational speed n = 382 rpm, test duration t = 500 s.

Figure 5 shows friction coefficient in the function of time at a load of 10N. This diagram illustrates the Cu-Mo coating before and after modification with a laser beam. Dry friction observed in the case of the coatings resulted in the transformation of the outer layer into a surface layer. This was mainly due to the sliding stresses and speed, and the interaction with the medium. The state stabilization of the anti-wear surface layer was observed. In **Figure 5**, one can see stabilization of the friction coefficient after 80sec., its value fluctuating at 0.16÷0.18. In the case of a laser modified Cu-Mo coating, the friction coefficient stabilizes after 240 sec., and its value fluctuates at 0.35÷0.37. The average friction coefficient of a Cu-Mo coating is lower than that of a laser-modified Cu-Mo coating (at the moment of stabilization).

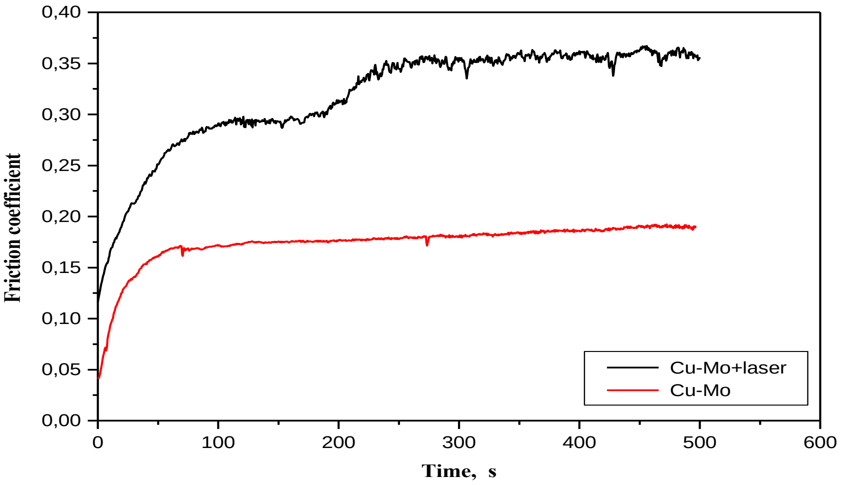


Figure 5 Relationship between friction coefficient and time

The corrosion resistance of the Cu-Mo coating and the underlying substrate before and after laser treatment was analyzed using a computerized system for electrochemical tests, Atlas'99, produced by Atlas-Sollich. The potentiodynamic method was applied, because it is reported to be one of the most effective methods of electrochemical testing. The cathode polarization curve and the anode polarization curve were determined by polarizing the samples with a potential shift rate of 0.2 mV/s in the range of ±200 mV of the corrosive potential, and with 0.4 mV/s in the range of higher potentials. Samples with a marked area of 10 mm in diameter were polarized up to a potential of 500 mV. The polarization curves were drawn for samples exposed for 24 hours to a 3.5% NaCl solution so that the corrosive potential could be established. The tests were performed at a room temperature of 21°C (±1°C).

The characteristic electrochemical values of the materials under test are presented in **Table 1**. The electro-spark deposited coatings were reported to have similar corrosion resistance to that of the substrate material. A system with a two-layer coating is assumed to fulfill two functions: increase corrosion resistance and wear resistance. The coatings which contained Cu acted as cathodes. Resistance to wear and corrosion depends on the quality of coatings, particularly their sealing properties.

Table 1 Current density and corrosion potential of the materials tested

Material	**Corrosion current density I_k (μA/cm^2)**	**Corrosion potential E_{KOR} (mV)**
C45	112 ± 17.8%	-458
C45+laser	86.4 ± 16%	-522
Cu-Mo	42.9 ± 11.8%	-620
Cu-Mo+laser	30.7 ± 2.6%	-629

The Cu-Mo coating was reported to have the highest corrosion resistance. The corrosion current density of the coating was 42.9 μA/cm^2, while that of the C45 steel substrate was 112 μA/cm^2. Applying the Cu-Mo coating improved the sample corrosion resistance by approx. 162%. There was some improvement in the corrosion resistance of the electro-spark deposited coatings after laser treatment. The healing of microcracks resulted in higher density and therefore better sealing properties. The highest corrosion resistance after laser treatment was reported for the Cu-Mo coating (I_k=30.7 μA/cm^2). For the C45 steel substrate, I_k was 6.4 μA/cm^2. Thus, the corrosion resistance increased by about 30 % after laser treatment. Laser treatment improved the surface smoothness and corrosion resistance; there was a decrease in the surface roughness, Ra, from 2.02 μm to 1.75 μm.

4. CONCLUSIONS

The following conclusions can be drawn from the analysis and test results.

1) There is no change in the chemical composition of electro-spark deposited coatings after LBM in spite of their melting and solidification. The results of laser radiation are the homogenization of the chemical composition, structure refinement and the healing of microcracks and pores.
2) LBM causes an improvement in the functional properties of the two-layer electro-spark deposited Cu-Mo coatings, i.e. they exhibit higher microhardness and higher resistance to corrosion.
3) Laser-modified ESD coatings perform anti-wear and protective functions, which enable their potential application in means of transport such as rolling stock.

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